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Smart Environment for Smart Cities: Assessing Urban Fabric Types and Microclimate Responses for Improved Urban Living Conditions

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1 ABSTRACT

Urban areas are particularly vulnerable to the impacts of climate change; they are also the chosen living environment of a significant majority of Europe‘s population. Global warming increasingly influences the urban climate and affects the future health and well-being of the urban population. The urban climate is mainly influenced by the urban form and the open space structure, which significantly modify the regional climatic conditions, and thereby directly affect the (thermal) comfort of the citizens. At the same time, urban open spaces are generally becoming more important as a result of their role in helping to support sustainable urban development from an ecological, social and economic point of view. Thus the future quality of life within cities is highly dependant on the “smart” treatment of its open space structure.

The objective of the present study within the ACRP 3rd call was to better understand the way in which the small scale structure of the urban fabric contributes differentially to heat island effects and other urban climate phenomena, and to use this information to develop specific strategies for counter-acting and mitigating these effects on a local basis. A major focus has been laid on the urban morphology and in particular the urban landscape, and on understanding its interaction with urban microclimate. The aim was to identify climate sensitive urban patterns – using the example of Vienna - and to suggest concrete open space design measures to counteract the overheating effect during hot summer days. On the basis of a grid used by Statistik Austria (quadrants of 500 m x 500 m) an urban fabric typology for the city of Vienna has been generated taking into account aspects of urban climate and urban structure with regard to terrain, open space and built structure, which influence the microclimatic conditions and parameters. The derived “urban fabric types” have been analysed, characterised, and a sample of the most critical types formed the basis for further investigation of potential open space design measures aimed at counteracting the overheating. This was undertaken using the microclimate simulation programme ENVI-met 4.0. The evaluation of the data generated has focused on thermal comfort and on its most relevant climate factors and has taken the form of maps, mean values and diurnal variations. Based on the evaluation of the simulation results and with regard to results of a previous project, a general catalogue of open space design measures has been compiled. Representative packages of measures have been defined for each sample quadrant, highlighting their specific conditions based on their open space patterns and climate sensitivity, and focused at obtaining the optimal influence on thermal comfort amelioration.

2 INTRODUCTION

Urban climate is generally embedded in regional climate conditions. But due to the built structure of the urban area and other anthropogenic influences, the urban climate can differ significantly from that of its surroundings (OKE 1987, ELIASSON 2000). A typical phenomena is the urban heat island effect caused amongst other things, by changed wind conditions due to building structure, by the use of building materials with a high thermal capacity, a high proportion of sealed surfaces and by increased air pollution exacerbating the greenhouse effect (KUTTLER 2009, WILBY 2007). The increased overheating has a direct influence on the health, well-being and thus the quality of life of the citizens (KEUL 1995). Besides aspects of usability and attractiveness of urban open space, there also exists a clear relationship between nocturnal heat stress, cardivascular deseases and the mortality rate (HUTTER et al. 2007). Against the background of global climate change, there is an urgent need for urban planning measures to ameliorate the local climate conditions and enhance thermal comfort, particularly within the densely populated city districts (MEEHL 2004, RAHMSTORF & SCHELLNHUBER 2007, HAGEN & STILES 2010).

The urban climate in general is made up of many local climates resulting from the individual small urban structures, which differ from each other with respect to their size, the surrounding built structure, surface materials, and the configuration of open space (GEIGER 1961, FEZER 1995). Thus the urban morphology – indeed the urban landscape as a whole – plays an essential role in influencing the urban climate in terms of counteracting the increasing overheating, as well as in adapting to the changing climate conditions (BROWN & GILLESPIE 1995, HAGEN 2011). The project lays the focus on this approach by classifying the whole city area of Vienna in specially generated urban fabric types, which influence the microclimatic conditions and parameters and integrate aspects of urban climate and urban morphology in terms of terrain, open space and built structure,

3 IDENTIFICATION OF CLIMATE-SENSITIVE URBAN FABRIC TYPES IN VIENNA

3.1 Generation of urban fabric typology

The generation of the urban fabric typology is based on a grid used by Statistik Austria which divides the whole city area into 500m x 500m quadrants. Data sets were compiled for each quadrant describing the above mentioned criteria urban climate, terrain, open space and built structure. In total around 250 indicators were extracted, 44 of which were selected to be used in the multivariate statistical analysis. The selection of the final indicators used was based on existing classification models, e.g. on the indicators used by ADOLPHE (2001) for his characterisation of urban structure for urban climate analysis and on the Stadtstrukturtypenansatz of PAULEIT (1998) with respect to urban open space patterns (Table 1).

Urban climate	Built space	Open space
	Density	**Surface condition**
air temperature	porosity	ratio of sealed surfaces
air humidity	occlusivity	capability and speed of infiltration
wind speed	compacity	soil moisture and water areas
wind direction	volume, surface/volume	heat absorption and retention capacity
precipitation	length of inner and outer fassades	surface temperature
global radiation	solar admittance	albedo
	contiguity	
Terrain		**Vegetation**
	Orientation	height of vegetation
absolute ground level elevation	sinuosity	density of vegetation
slope gradient	orientation of facades	cover ratio
slope orientation	orientation of streets	
positioning of summits and hollows		
	Rugosity	
	absolute rugosity	
	relative rugosity	
	wind shadow	

Table 1: Indicator groups and most important criteria considered for the generation of the urban fabric types

The four thematic groups were analysed using factor analysis in order to eliminate redundant information and to identify the most influential parameters. As a result, a certain number of factors for each group was selected to serve as “super variables”, containing the information of the entire indicator set. The data subset “urban climate” was represented by one factor, the data subset “terrain” by two factors and the last two subsets “open space” and “built structure” were represented by three factors respectively.

A „two-step“ cluster analysis was carried out to classify the quadrant and into urban fabric types (UFT) which reflect the overally variation of Vienna’s urban landscape on the basis of the criteria described above. The cluster analysis resulted in 9 urban fabric types, each representing a combination of physical morphology and climate sensitivity. The urban fabric types which appeared to have the most potential to be explored further were those represented by clusters 1 to 5 and 8 (see Fig. 1). These urban fabric types were more vulnerable to certain impacts of climate change (due to the high proportion of sealed surfaces, the low proportion of green open space, the high number of hot summer nights, etc.), and were therefore the most promising targets for future mitigation measures. Although the selected clusters characterising the city's urban fabric types generally presented a convincing representation of Vienna's urban morphology, a further attempt was made to see, if it were possible to resolve the urban structure in greater detail by further sub-dividing some of the more heterogenous classes – in particular urban fabric types 2 and 3, and type 6, the Danube river corridor. Further analysis of these clusters was therefore conducted, leading to the generation of another three 'sub-types' for each one. Figure 1 shows their distribution across the city.

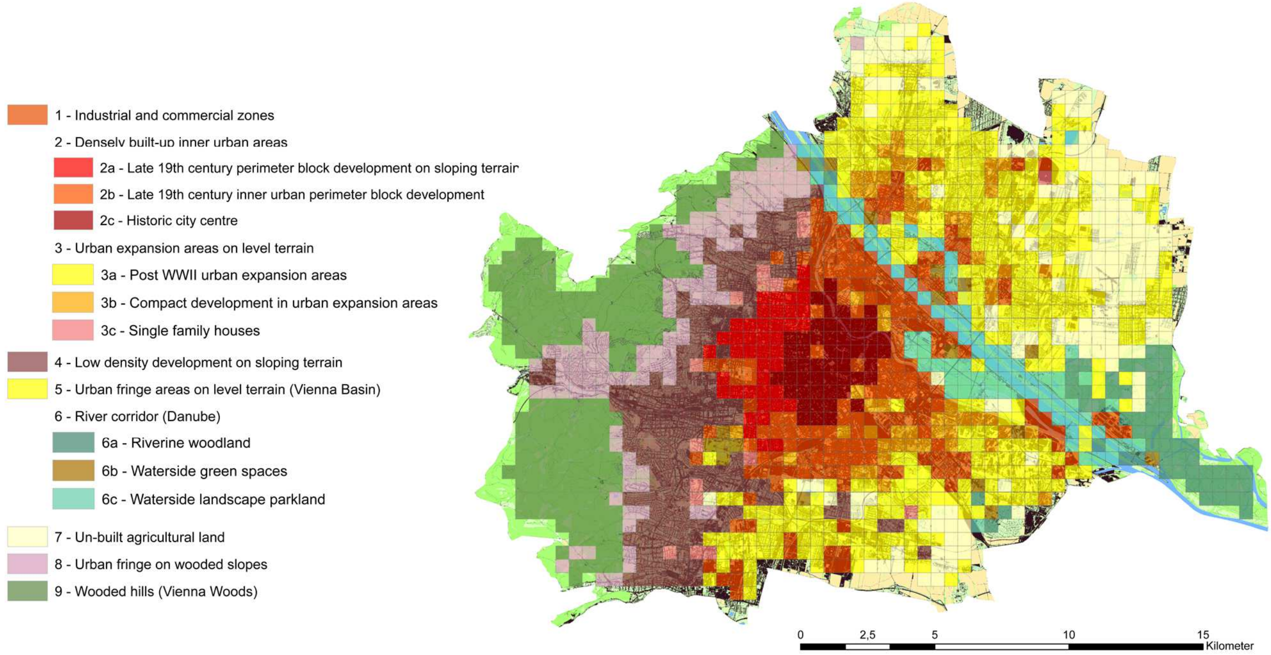

Fig. 1: Urban fabric types (UFT) for Vienna including the subclusters of UFT 2, 3 and 6.

3.2 Selection of urban fabric types for further investigation

For further investigation, the focus was laid on those urban fabric types and sub-types which were likely to be the most climate-sensitive, namely those within the dense inner urban areas and the main urban expansion areas northeast of the Danube:

UFT 1 - Industrial and commercial zones: marked by heterogenous building structure and a high percentage of sealed surfaces; dominated by perimeter block development and multi-storey linear housing; big industrial zones with generous areas of green space, and a strong influence of urban heat island phenomena.

UFT 2 - Densely built-up inner urban areas: with the highest percentage of sealed surfaces and the greatest building heights; historic building structure (especially perimeter block development) with a low proportion of green space; the highest number of hot nights and the warmest winters.

- 2a - Late 19th century perimeter block development on sloping terrain: marked by perimeter block structure and about 86% sealed surfaces; elevations in the terrain structure; low proportion of green space dominated by taller trees and grass areas; hot with highest amount of precipitation within the sub-types.
- 2b - Late 19th century inner urban perimeter block development: marked by perimeter block structure and high proportion of sealed surfaces; only small differences in elevation; green structure dominated by grass areas and small trees; hot, especially high number of hot summer nights.

UFT 3 - Urban expansion areas on level terrain: marked by heterogeneous building structure and a high proportion of grass areas and agricultural land; high amount of sealed surfaces on level terrain; a moderate amount of shrubs and small trees; highest number of hot summer days, but with cooler nights.

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- 3a - Post WW II urban expansion areas: marked by detached housing zones and an average building height of 6m; low building density; about 50% sealed surfaces; high proportion of grass areas (particularly agricultural areas) and low tree structure; hot days and warm nights.
- 3b - Compact development in urban expansion areas and old village centres: marked by heterogeneous building structure with an average building height of 11m; highest building density within the sub-types; high proportion of sealed surfaces; warm days and warm nights.

4 OPEN SPACE AND MICROCLIMATE CHARACTERISTICS

4.1 Selection of representative sample quadrants

A selection of sample quarter kilometre square quadrants within each of the selected urban fabric types was made in order to investigate their microclimatic characteristics as a function of their morphology. The quadrants were selected according to their climate sensitive open space patterns and as representatives of average indicator values for each of the respective urban fabric types. The final selection of sample quadrants took place in several steps (Fig. 2):

(a) statistical analysis was undertaken to obtain a significant number of samples representative of a particular urban fabric type. The number of samples chosen depended on the number and spread of quadrants within an urban fabric type;

(b) the selection of representative sample quadrants for each fabric type for further analysis and simulations. Here the main focus was on the identification of typical urban open space patterns, making use of information from the Grünraummonitoring (green space monitoring) and the Flächenmehrzweckkarte (digital map) databases, which were integrated using ArcGIS. The most representative quadrants were identified by making use of the spatial characteristics data, focussing on those categories covering at least 5% of the total quadrant area; and

(c) the comparison of aerial photos of the most representative quadrants for the final selection in order to assure the applicability of the simulation method (e.g. localisation of important open space patterns within sample quadrant and avoiding falsification of simulation results due to boundary effects).

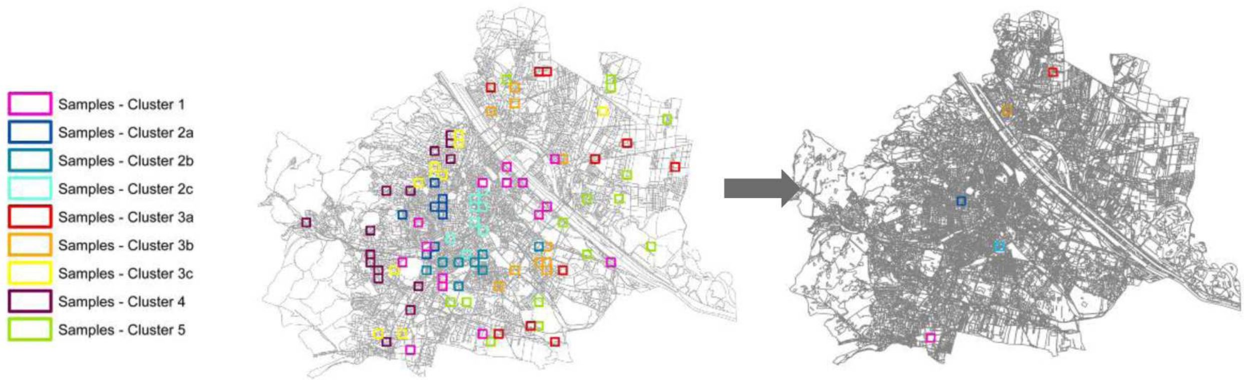

Fig. 2: Statistical random sample and final selection of sample quadrants for further investigation.

4.2 Analysis of open space structure and microclimate conditions

Typical urban open space patterns were identified for each urban fabric type as represented by the selected quadrant, by means of the analysis of rectified aerial photos, which were compared with the databases referred to above. This lead to a classification with respect to potential open space design measures in which the main categories were: road system (linear street area or widenings), courtyards (fragmented within block or entire block), green areas (fragmented, connected or extensive), squares (fragmented, connected or extensive), other areas (car parking, paved areas within industrial sites, rail tracks, waste land or agricultural land) and potential roof areas for greening. The open space structures identified were digitized for all the sample quadrants using ArcGIS, thereby making possible a quantative analysis of the percentage distribution characteristic of each urban fabric type. The keywords relating to the respective characterisation are presented in Table 2.

The microclimate conditions of the status-quo of each selected quadrant were simulated using the programme ENVI-met 4.0 (BRUSE 1998). ENVI-met is a three-dimensional computational model for analysing small scale interactions between urban structure and mircoclimate. The model combines the calculation of fluid dynamics parameters such as wind flow or turbulence with the thermodynamic processes taking place at the ground surface, on walls and roofs or in vegetation. A big advantage of this simulation programme is the possibility to present the results in form of maps and vertical sections, facilitating the understanding and explanation of climate issues for non-experts. The atmospheric input data used for the simulations referred to current extreme climate conditions using a hot summer day, measured in the inner city of Vienna, representing the 99th percentile of the daily maximum air temperature. Further simulations were conducted for projected future climate conditions for the year 2050, based on results from the regional climate model COSMO-CLM (LOIBL 2010). These showed that the current climate sensitivity will increase significantly, emphasising the urgency of taking counter-measures immediatly.

The simulation results were compared to the maps of open space structure and reviewed with regard to the typical and critical climate situations. Comparable open space patterns within the different quadrants which had been selected, demonstrated different climate sensitivity due, for example, to their particular proportions. Open spaces with sealed surfaces heat up strongly, while green open spaces with ground-cover vegetation and trees result in the lowest temperatures and the highest comfort values. However, even within green courtyards, sealed areas form hotspots, which result in clearly identifiable thermal discomfort zones especially during the afternoon. Critical areas within the dense urban structure could also be located, for example, in areas where the streets are wider and where there are junctions. Figure 3 is an example showing the open structure map (left) and the simulation map for the PMV (predicted mean vote) as a value representing thermal comfort (right) for sample quadrant 723, which lies on the border of the 16th and 8th districts of the city, and is representative for urban fabric type 2a. The areas of highest heat stress (magenta) are clearly located along the street areas and street widenings, particularly within west-east-orientated streets as well as on crossings and squares. The small and fragmented courtyards show lower heat stress (green) due to shading by the surrounding buildings. The lowest thermal load is to be found in entirely green courtyards and within the planted street areas with tall trees along the Gürtel (Fig.3).

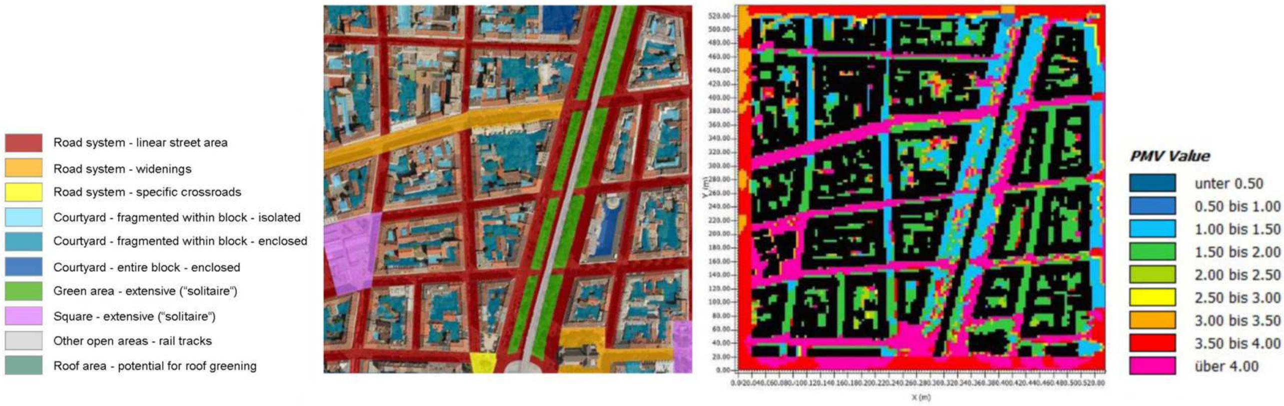

Fig. 3: Maps for open space structure and status-quo climate conditions for sample quadrant 723 (UFT 2a).

5 POTENTIAL OPEN SPACE DESIGN MEASURES

The characterisation of the sample quadrants led to adjusted design measures which were used in further simulations aimed at the amelioration of thermal stress, including tree planting, de-sealing of impermeable surfaces and roof planting where appropriate (based on the Gründachpotentialkataster). According to the specific conditions of each sample quadrant, the design variants were focused on different aspects such as street orientation and width, the influence of density and of adjacent areas, etc. The evaluation of the generated data has focused on thermal comfort and on the most relevant climate factors that influence it, in form of maps, mean values and diurnal variations.

5.1 Design measures

Based on the input files and results of the status quo simulations, different design variants were defined and modelled using ENVI-met 4.0 to investigate the respective microclimatic effects.

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The modelled design variants were:

- different forms of tree planting with respect to appropriate measures for the identified critical climatic aspects within each open space type. The implementation of tree planting with regard to the type (deciduous), size (crown diameter 12m) and planting distance (canopy closure) was based on the results of a previous project (FREIRAUM UND MIKROKLIMA 2011).
- the de-sealing of paved surfaces within the affected open space types. This involves a simple change of surface material as well as potential structural changes e.g. the transformation of certain traffic lanes to public space.
- the implementation of extensive roof planting based on the data of the "Gründachpotentialkataster" (green roof potential map).

The design measures were simulated individually and in appropriate combinations, allowing conclusions to be drawn regarding specific open space situations, including an "optimal variant" over the entire area of the sample quadrant. According to the characteristics of each sample quadrant, the focus of the design measures was adapted correspondingly (Table 2).

SQ	UFT	Open space structure	Focus of design variants	Variants
555	1	characterised by extensive paved surfaces and parking areas, high potential for roof planting	de-sealing of ground surfaces in extensive paved areas as far as reasonable, de-sealing of ground surfaces together with tree planting along building sites and on parking areas, area-wide extensive roof planting	4
723	2a	characterised by orthogonal road system (N, W) and fragmented, partially connected courtyards	tree planting along the streets with focus on street orientation as well as on the respective street sides (facades)	5
919	2b	characterised by orthogonal road system with widenings (NW, NE), rail tracks and adjacent in-plant areas as well as all types of courtyards and extensive green area.	tree planting along the streets with focus on the south façade along the Gürtel-road, de-sealing of ground cover within street widenings and possible abandoning of street section along the Gürtel-road, de-sealing of parking and in-plant areas as far as reasonable, de-sealing and tree planting within larger-scaled courtyards	10
983	3a	characterised by linear street area with crossroad widenings, opened courtyards, connected green areas and parking area.	tree planting along the streets with focus on crossroad widenings, de-sealing and tree planting in possible abandoned street sections, de-sealing and tree planting within parking areas	9
1264	3b	characterised by linear street area, fragmented green area and agricultural land	tree planting along the streets with focus on street orientation as well as on the respective street sides (facades), de-sealing and tree planting within parking area	6

Table 2: Open space characteristics and measures focus on the microclimate simulations for the sample quadrants

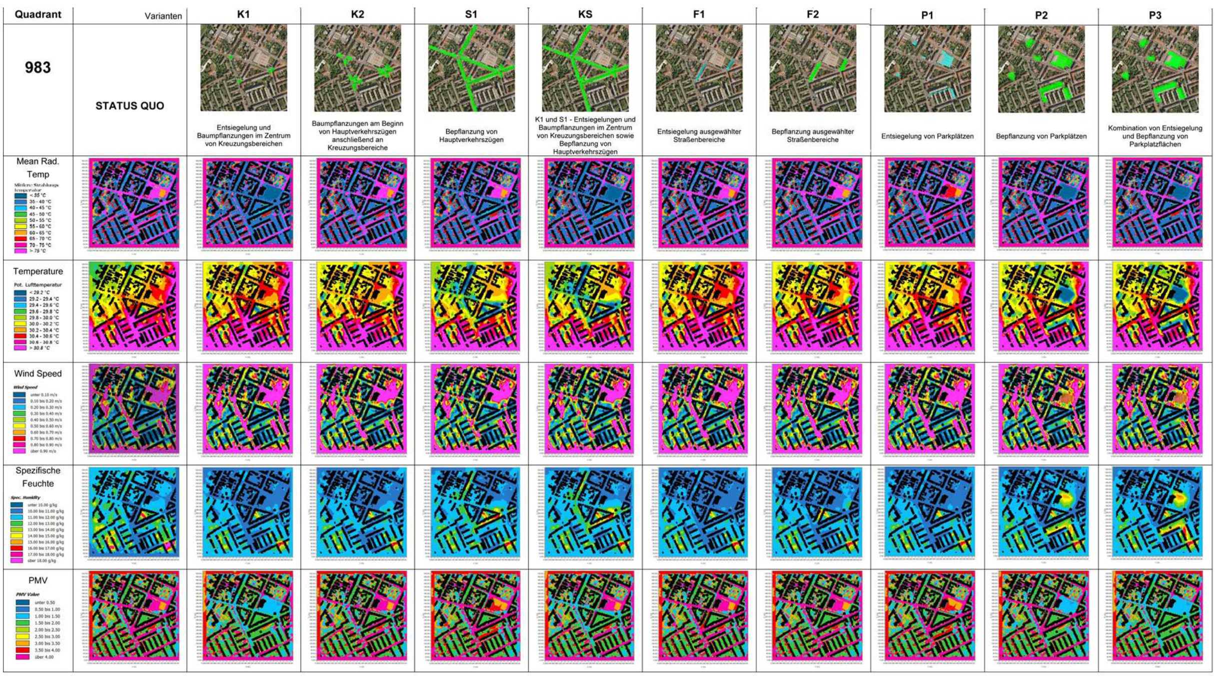

Fig. 4: Maps for open space structure and status-quo climate conditions for sample quadrant 983 (UFT 3b).

5.2 Simulation results

The simulations of the design variants were conducted using ENVI-met 4.0 under conditions identical to the status-quo simulations, involving 36 hour run time durations and focussing on hot cloud-free summer days with a high temperature amplitude. The resulting data was analysed using simulation maps, extracted mean values and diurnal variations. The focus was placed on the PMV value, which also takes into account effects of wind speed, mean radiant temperature, potential air temperature and humidity. Figure 4 provides an exemplary overview of the simulation maps generated for the different variants of sample quadrant 983 in the 21st Vienna district, and representing urban fabric type 3b. The focus of the design variants was laid on the tree planting along the main streets with special focus on road-junction widenings, de-sealing impermeable surfaces and tree planting in potential abandoned street sections, as well as de-sealing impermeable surfaces and tree planting within parking areas.

Simulation results for the design variants within the investigated sample quadrants can be summed up broadly as follows.

- Generally, tree planting shows the greatest effect on all design measures analysed, especially within the immediate area covered directly by the tree crown. The PMV value is reduced from “extreme hot conditions” to “slight warm conditions”. A clear correlation can be observed with the specific pattern of tree distribution in relation to the adjacent open space structures and to the width and orientation of the respective open spaces. The simulations for sample quadrant 723, for example, highlight the importance of considering the street orientation, and show a much greater effect in reducing temperature values due to tree planting along the east-west oriented streets as compared to streets oriented north-south. For the same quadrant, the diurnal variations with regard to different microclimatic factors of the status-quo situation as compared to the design variant of street planting in the east-west orientated streets show a significant decrease in the mean radiant temperature, and a similarly significant increase in the specific humidity. Although the wind speed is slightly reduced, the air temperature can be reduced up to 1.5°C during the hottest period of the day and by 3°C at night.
- Just de-sealing the ground surface generally results in a slight reduction of the PMV value particularly during the hottest time of the day, around 3 p.m. This could be clearly observed in all sample quadrants especially in the case of the de-sealing of impermeable parking areas and industrial zones, for example within sample quadrant 919, which is located in the 4th Vienna district and marked by perimeter block buildings adjoining a vast area of sealed surfaces to the north, including the Gürtel, rail-tracks, parking and industrial areas. Looking at the respective differential maps of diurnal variation, further microclimatic effects become apparent. A significant cooling of the air temperature within the adjacent resident area to the north-west can be observed as a result of the south-easterly wind conditions.
- The roof planting generally has less direct influence at ground level. Looking at the vertical distribution of microclimatic data, the amelioration effect is highlighted. The vertical section of the potential air temperature for the design variant involving roof planting for quadrant 555 in the 23rd Vienna district, which is characterised by low, flat-roofed, industrial and commercial buildings illustrates a significant cooling effect at higher air levels and in the leeward direction from the buildings.

6 PLANNING RECOMMENDATIONS

The results of the simulations were evaluated with respect to the overall open space patterns, leading to general recommendations and to specific packages of measures for each sample quadrant and the corresponding urban fabric type.

The catalogue of general recommendations (Maßnahmenkatalog) was formulated according to the type of design measures concerned: tree planting, de-sealing of ground surfaces and roof planting. Additional information and recommendations are given based on a literature review and on the results of a previous project, dealing with aspects of tree size, species, distribution, distance of planting and different forms of de-sealing the ground surface (FREIRAUM UND MIKROKLIMA 2011).

According to the characteristic open space structures within the respective sample quadrants, specific packages of measures (Maßnahmenpakete) were defined based on their effectiveness, thereby establishing a hierarchy of priorities. Each urban fabric type was briefly characterised in terms of its topography, the urban structure and climatic conditions. The respective sample quadrants were discussed in terms of their percentage area, of their existing open space patterns, and their representative status for the urban fabric type as a whole. Based on the general recommendations in the catalogue, specific packages of measures have been defined for the respective open space structures. These have been set out in the form of priorities that take account of, the climatic effect of the recommended measures (locally as well as on the nearby surroundings), their potential for implementation (with respect to limitation of adaptable surfaces due to logistic aspects, and to the degree of additional benefit to be expected, depending on the status-quo situation) and to the potential user intensity within the open space structures concerned. A second hierarchy was also developed with the additional consideration of the percentage distribution of the respective open space structures within each of the quadrants. This showed up interesting variations that enable alternative approaches to concrete implementation to be evaluated. Figure 5 provides an example of the percentage distribution of open space structures within sample quadrant 555 as representative of urban fabric type 1 (Industrial and commercial zones) leading to the package of recommendation in Table 3.

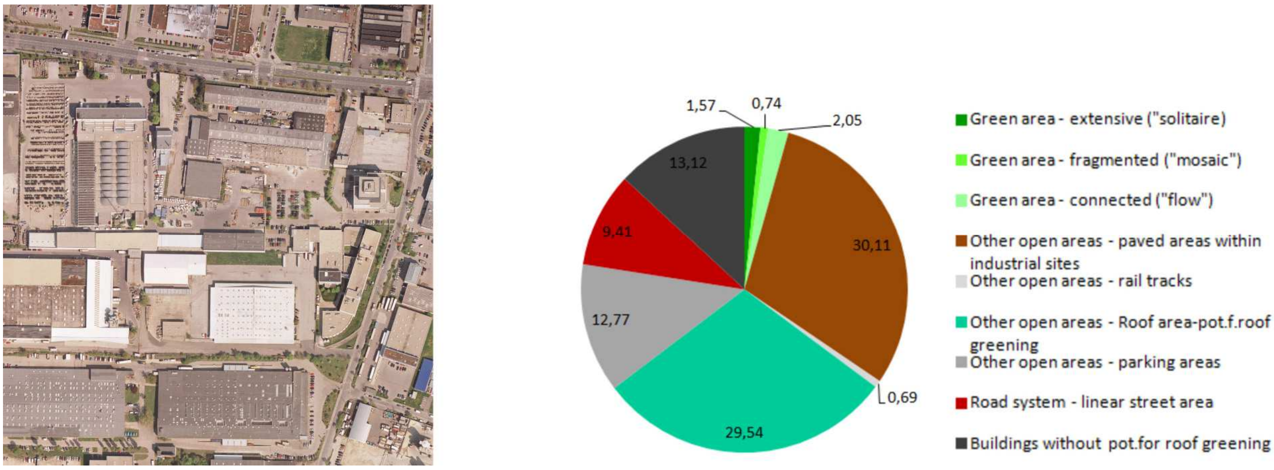

Fig. 5: Percentage distribution of open space patterns for sample quadrant 555.

Priority	Open space structure	Design measurement	Area	Priority*
1	**Parking areas** (grey)	**De-sealing and Tree planting** (area-wide)	13%	2
2	**Roof area with potential for roof planting** (green)	**Roof planting** (area-wide) Where statically and technically feasible preferably intensive roof planting as to its greater microclimatic effect and offering of aditional green space for workers and residents	30%	1
2	**Linear street area** (red)	**Tree planting** Focus on wide streets and on east-west orientated streets	9%	3
3	**Paved areas within industrial sites** (brown)	**De-sealing and Tree planting** (as far as posible) De-sealing area-wide except areas of stacking, heavy load and hazardous contaminant Tree planting particularly along the property lines and in front of buildings	30%	4

Table 3: Package of measurements for sample quadrant 555 as representative for UFT 1 in order of priority considering climatic effect, potential for implementation and potential user intensity (left column) resp. additionally percentage area (right column).

7 CONCLUSION

The urban space typology shows close agreement with similar city typologies addressing other criteria, as well as reflecting the relationships between urban structure and urban climate pattern. The characterization of different urban space types, on the basis of the sample quadrants investigated also illustrates the close interrelationship between open space structure and the local climate conditions. The analysis of the microclimate simulations demonstrates the effects of various design measures. Planting trees helps - in addition to the increase in transpiration - by enlarging the shaded area and thus reducing the extent of areas exposed to high mean radiant temperature. Taking into account the effects of all times of day, treeplanting causes a significant reduction in mean radiant temperature, but also in air temperature. The minimum, maximum and mean air temperature is reduced. The minimum air temperature occurs earlier than without tree plantings. De-sealing of large areas of impermeable surfaces can cool down the air temperature within neighouring dense city quarters downwind of the prevailing wind direction. Roof planting equally has a cooling effect downwind of the wind direction, particularly when implemented on lower buildings. Furthermore, in quadrants with similar open space characteristics, differences could be identified due to local variations in the urban fabric (orientation, height:width ratio, adjacent land or buildings, etc), leading to the recommendation of different priorities with regard to design measures. The results can serve as a planning guideline and to provide decision support for urban design and should create greater awareness of the need for climate sensitive open space design, given appropriate presentation of measures and impacts. The results have to be confirmed with regard to their replicability in other studies. But one can be optimistic that the study can serve as a basis and a model for further investigations in cities throughout Europe, with the aim of improving local thermal comfort. Additional work will be necessary to investigate the detailed costs and benefits of the proposed measures.

8 ACKNOWLEDGEMENTS

The paper presents the project “Urban fabric types and microclimate response - assessment and design improvement” within the ACRP 3rd call. The detailed results and the complete catalogue of recommendations can be found in the final report that is available for download on the official website www.urbanfabric.tuwien.ac.at (STILES et al. 2014). Project coordinator: Vienna University of Technology, Institute of Urban Design and Landscape Architecture (Prof. Richard Stiles, Dr. Katrin Hagen, Dipl.-Ing. Beatrix Gasienica-Wawrytko, Dipl.-Ing. Heidelinde Trimmel). Project partners: Austrian Institute of Technology, Energy Department (Dr. Wolfgang Loibl, Dr. Tanja Tötzer), TU München, Strategic Landscape Planning and Management (Prof. Stephan Pauleit). Special thanks to Mag. Mario Köstl (AIT) for the data processing and to Dr. Wolfgang Feilmayr (Vienna University of Technology) for the statistical assessment.

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